RELIABILITY EVALUATION OF SOLAR PHOTOVOLTAIC POWER SYSTEM

A Synopsis submitted

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by

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LIST OF CONTENTS

List of content i

List of figures i

List of abbreviations ii

1 Introduction 1

2 Literature Survey 5

2.1 Power Generation System 5

2.2 Distribution networks 7

2.3 Grid integration of PVs 8

2.4 Power electronic components 10

3 Scope of the work 12

References 14

LIST OF FIGURES

1.1 Subdivisions of power system reliability 2

1.2 The possible components of a photovoltaic system 3

2.1 Schematic diagram of a PV power system using central inverters 6

2.2 Electrical architecture for the PV system 10

2.3 Power electronics components which are used in a PV system 11

LIST OF ABBREVIATIONS

PV	Photovoltaic
ELCON	Electricity Consumers Resource Council
LOLE	Loss of Load Expectation
EUE	Expected Unserved Energy
RBTS	Roy Billinton Test System
NREL	National Renewable Energy Laboratory
MRM	Markov Reward Models
CHP	Combined Heat and Power Plants
FTA	Fault Tree Analysis
DG	Distributed Generator
LHS	Latin Hypercube Sampling

1. Introduction

The foremost important objective of an electrical utility is to deliver economical, reliable, and quality power to its customers. The electrical energy has seen monotonically increasing demand over the decades and still continuing to grow. The failure of power has significant socio-economic impact on utility and its customers. While great emphasis is given to reliability of supply, which runs businesses and essential services such as hospitals and communications networks, failure in power system is random, sometimes outside of the controls. The electrical power network is very complex; a failure may result in loss of power to a large number of customers or sometimes catastrophic events such as blackouts. The effect of failure may not just be limited to revenue loss to utility and supply interruption to customers but can indirectly affect the society and the nation. The Electricity Consumers Resource Council (ELCON) report [1] about August 14, 2003 blackout reports power failure to 50 million people and failure cost between $7 Billion - $10 Billion. Therefore, reliable power system operation and design is very important.

Sources of renewable energy have become increasingly popular in recent years due to environmental concerns resulting from fossil fuel consumption in conventional power plants. The conventional power generators are mainly gas turbines and steam turbines. Till now, it is not possible to completely replace the conventional sources with renewable sources. Although, a mix of these is a viable solution, the generation mix is changing with the rapid growth in the number of renewable power plants such as solar and wind.

Solar photovoltaic (PV) is widely used as renewable energy source to provide electricity power to consumers. Solar PV can convert free and unlimited sunlight to electricity without carbon dioxide emission or any other air pollutants. Given these advantages, large-scale solar PV generation has been gradually integrated into power grids to serve energy need. When the utility company plans to install solar PV generation in their system, both installation capacity and location of PV are the main concerns. Due to the uncertain characteristics of sunlight, the solar penetration level in a system is usually limited by some reliability constraints. In this research, the system performance

of PV penetration at specific location would be simulated by Monte Carlo simulation and the probability of contingency consequences would be determined through contingency analysis. When designing the optimal PV size in a system with minimum cost, the result of the system reliability evaluation can be directly used as the optimization constraint in order to meet system reliability requirements.

In general term "reliability" is defined as probability of device or system performing its purpose adequately for the intended operating period of time [2]. Power system reliability is defined as ability of electrical power system to supply the system load with reasonable continuity and quality of supply. The definition of reliability is very vast and covers all aspects of supplying reliable power to consumers. Major subdivisions of power system reliability are 'system adequacy' and 'system security' as shown in Fig.1.1. The term adequacy relates to the existence of sufficient facilities within the system to satisfy the consumers' load demand and system operational constraints. This includes the facilities required to generate sufficient energy and the associated transmission and distribution facilities to supply energy to the consumers. Thus, adequacy mainly deals with static conditions and not the dynamic and transients of power system. Security is associated with system dynamics and disturbances in the system.

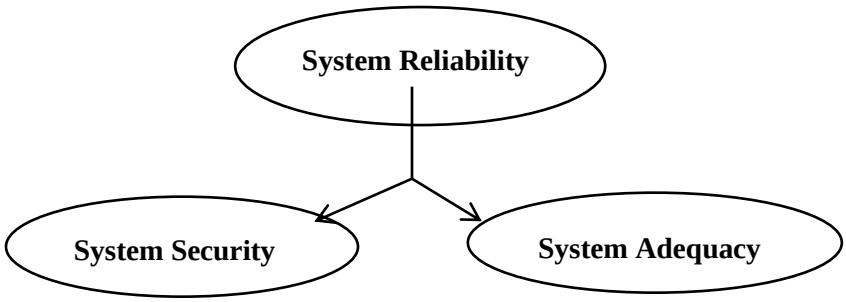

Fig. 1.1 Subdivisions of power system reliability

Reliability analysis techniques are well developed [3, 4] and have been applied to the conventional power systems. The reliability analysis techniques have been conventionally developed for synchronous generators. Later on, with the use of renewable natural resources such as wind and solar photovoltaic, the conventional reliability techniques were modified to take into account time varying nature of these generation sources [5, 6].

Electricity generated from photovoltaic (PV) power systems is a major renewable energy source which involves zero greenhouse gas emissions and no fossil fuel consumptions. The total capacity of grid-connected PV power systems have grown exponentially from 300 MW in 2000 to about 21 GW in 2010 [7]. Solar power in India is a fast developing industry, with a cumulative installed grid connected solar power capacity of 8,062 MW (8 GW) as of 31 July 2016. As a result, the capacity is increased by 187 times to the capacity 2010-11 and is planned to increase to 100 GW by 2020. A 60% average annual growth rate of PV capacity has been seen from 2004 through 2009, and an 80%–90% growth is anticipated in 2011. Highly reliable PV power systems, therefore, will greatly increase renewable energy output, guarantee higher return on investment, and help curtail carbon emissions globally. There are a number of auxiliary components other than PV solar panel, in a PV generation system, as shown in Fig.1.2. Similar to any other electrical systems, grid-connected PV power systems can fail because of accidental events and occasional failures in its components, resulting in significant amounts of economic loss [8]. Hence the reliability of grid-connected PV power systems has been of great concern to both utility companies and customers [9].

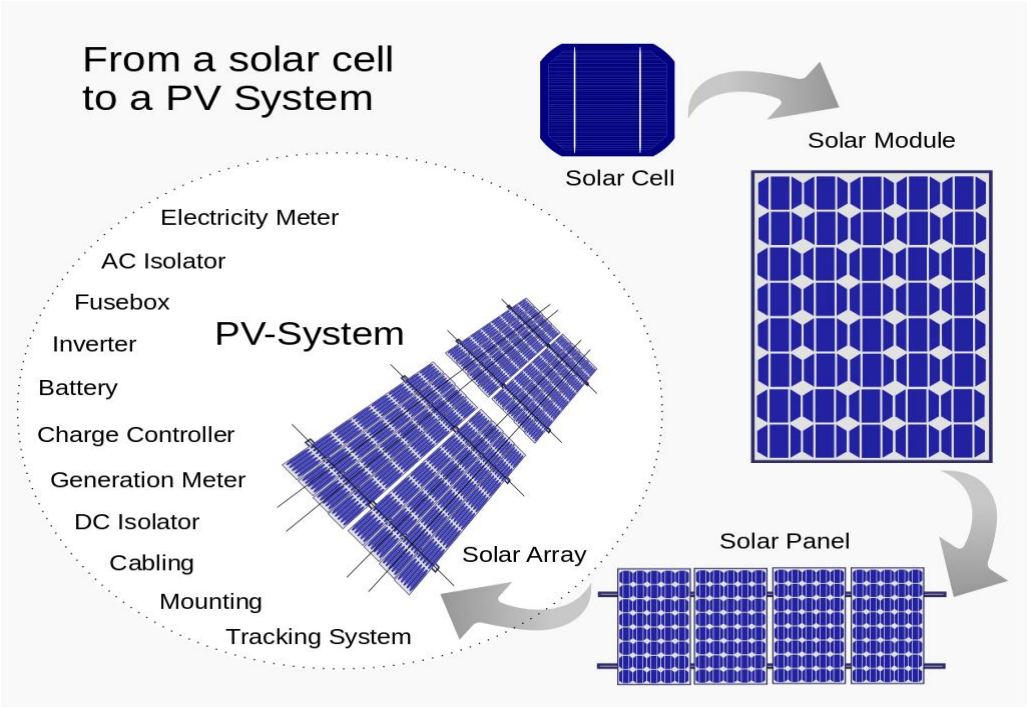

Fig 1.2 - The possible components of a photovoltaic system

Relatively high risks exist both inside and outside of PV power systems [10]. High uncertainty and variability associated with the system components and environmental factors pose major challenges in designing large PV power system [11]. First, a PV power system is composed of many vulnerable components [12, 13] whose lifecycle reliability is highly susceptible to temperature, power losses, and ambient environments. Meanwhile, solar insolation and power input of PV system are highly variable and uncontrollable; leading to high electrical stress in PV panels that may shorten the operational lifecycles and power electronic interfaces and consequently results in lower system reliability compared to conventional generation sources. Second, high penetration of PV generation will bring detrimental effect to power distribution network.

Distribution networks connected with PVs, therefore, have a high risk for increased maintenance costs and power outages, which necessitate methodologies and tools to quantify the reliability of grid-connected PV systems.

Risk assessment and reliability evaluation is of fundamental importance for planning and operation of both PV power systems and PV-connected distribution networks. Its major utilities include:

1) Quantifying risks in PV systems and choosing optimal PV system design.
2) Determining effective measures to mitigate risks.
3) Justifying acceptable PV penetration level in distribution network.
4) Probabilistically evaluating the impacts of intermittent PV resources on power system adequacy, security, spinning reserve, planning and real-time operation.
5) Designing reconfigurable distributed energy storage to leverage PV application.
6) Finding planning and operational solutions to address the challenges of high penetration of PV to distribution network in a least cost manner while achieving the maximum level of reliability.

Practical applications of PV risk assessment and reliability evaluation will bring direct and indirect benefits for both utility companies and customers including increased revenue, higher energy yield, improved power quality, extended equipment operational life and less carbon emission.

2. Literature Survey

Reliability evaluation techniques are well developed and various papers articles and books are published on this topic. Analytical and probabilistic techniques are in use for many decades. The development of reliability evaluation technique was associated with the aerospace industry and military applications [2]. It was subsequently followed by applications in nuclear industry and electric power systems where system failure has large social and economic impacts. The first large groups of papers on probabilistic methods were published in 1947[3]. The Markov chain method was used in reference [3] but that needs lots of computer storage and cause approximation error. Advances in reliability evaluation using Monte Carlo sequential simulation has become popular in later decades [4]. The reliability analysis of intermittent sources of power has been evaluated in [5, 6].

A detailed study of the research papers, books, reports etc. available in this area has been carried out. The different frameworks under which the literature survey has been performed are given below:

- Power Generation System
- Distribution networks
- Grid integration of PVs
- Power electronic components

The important papers and their contributions belonging to each framework are discussed below one by one.

2.1 Power Generation System

There are many papers that deal with unpredictability of renewable sources. These studies use historical weather and load data to predict the power generation and load on hourly basis. The correlation between generation and load needs to be considered. Ref. [14] develops a methodology for photovoltaic system reliability and economic analysis. This methodology is based on load reduction approach. This paper also does not take into account the failure characteristics of photovoltaic system. The reliability modeling of

generation systems including unconventional energy sources is studied in [15]. It considers two unconventional sources: wind and photovoltaic power plants. This paper calculates the loss of load expectation (LOLE) and frequency of capacity deficiency on hourly basis for the generation system. It does not, however, calculate the expected unserved energy (EUE). An efficient technique for reliability analysis of power systems including time dependent sources is developed in [16]. It uses the clustering technique to calculate the LOLE and EUE. This paper does not address frequency calculations. Ref. [17] develops a method for calculating expected unserved energy in generating system reliability analysis. It introduces the concept of expected value or mean value of capacity outage. This is used to calculate the LOLE and EUE on hourly basis, but in a more efficient way than given in [15]. It does not, however, calculate the frequency of capacity deficiency.

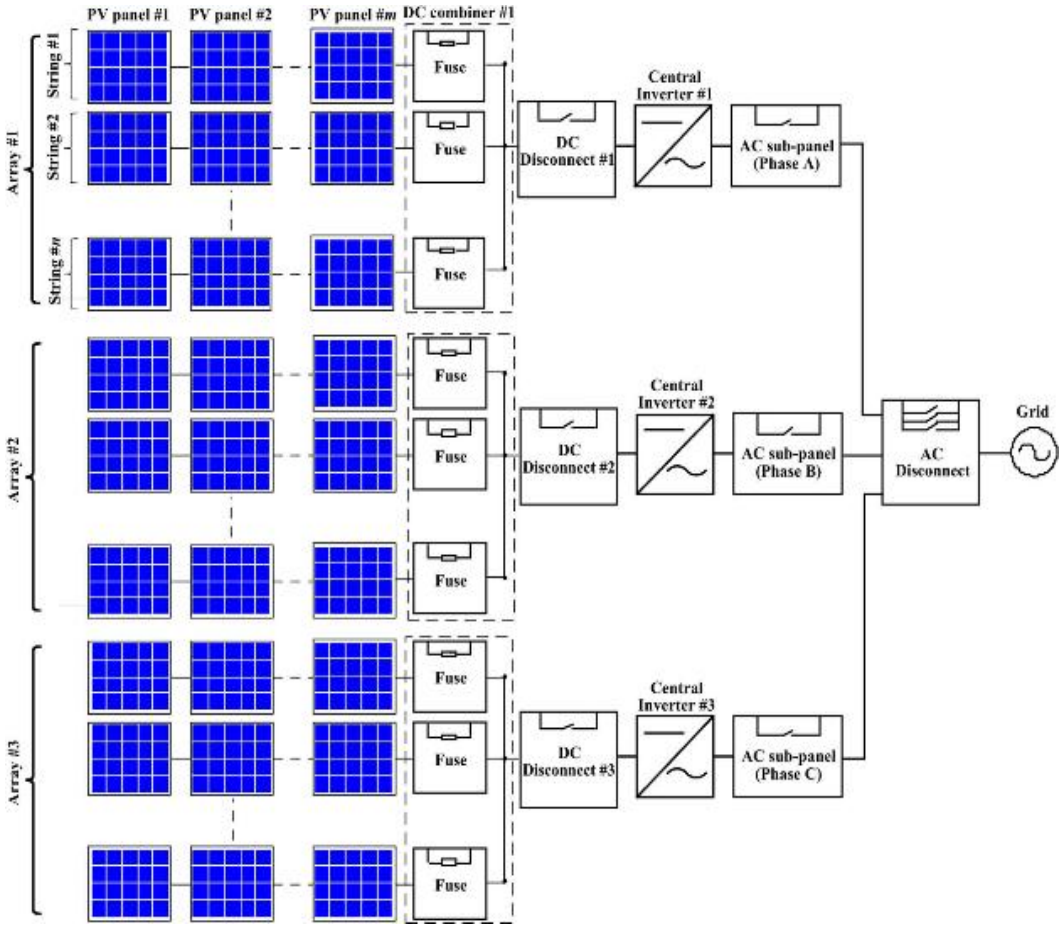

Fig. 2.1 - Schematic diagram of a PV power system using central inverters

Reliability evaluation of grid-connected photovoltaic power systems has been studied in [18]. It analyses component failures in utility scale PV power system, but it does not address the reliability impact of PV on the overall generation system.

The overall picture of a large grid-connected PV system is investigated first, before going into details of PV reliability assessment. As shown in Fig. 2.1, the three-phase central inverter PV system consists of three PV arrays.

2.2 Distribution networks

Reliability assessment of distribution networks with distributed generation has drawn attention of researchers in power systems engineering. Many researchers have analyzed distribution systems with renewable resources such as solar and wind energy. In order to implement these resources in reliability studies, a stochastic model of output power must be used. Output power models of stochastic energy resources such as solar radiation and wind energy have been developed by A.K David [19]. His work represents probabilistic methods to predict the fluctuation of these resources for the purpose of reliability studies in power systems. Khallat and Rahman in [20] have studied three different methods to predict the output power of photovoltaic systems, which are Normal, Weibull and Beta distribution. They have compared the obtained results in different seasons from these methods and recommended using Beta and Weibull to represent the intermittency of the solar insolation depending on the desired time. Sutoh, Suzuki and Sekin have developed a probabilistic model of PV output power [21]. Their model represents the average and the variance of the output power of PV. Meteorological data has been collected and compared with the results that were obtained from the model which has proven that the variance of the output power obeys a normal distribution.

Billinton and Wang in [22] have developed an algorithm to evaluate the reliability using MCS to be used in complex distribution networks. The program was used on the distribution system of the RBTS, and the obtained results were very close to the analytical method. Reliability evaluation of distribution networks containing microgrids have been studied by Bea and Kim in two cases [23]. The load duration curve model was used in the one case and the peak load was used in a second case to investigate the impact

of the load profile on system reliability. Huishi, Jian and Sige in [24] have investigated the impact of the distributed generations and storage systems on the distribution system reliability.

2.3 Grid integration of PVs

On the topic of grid integration of PVs, the National Renewable Energy Laboratory (NREL) has conducted extensive surveys to explore the impact of high penetration PVs on power system planning and operation [25]. It has been identified that PV integration is closely tied to overall distribution system reliability [26]. Recently, a framework, which is based on Markov reward models (MRM), is proposed to integrate reliability and performance analysis of grid-tied PV systems [27]. This proposed framework may help understand the trade-off between repair policies and replacement/overhaul costs. In addition, the effect of reactive power shortage on the distribution network with high PV penetration has been studied [28]. In the era of smart grid, the microgrid is a mainstream solution for grid integration of PV systems. Reliability evaluation of active distribution systems including PV microgrids becomes a major technical challenge to be tackled.

In previous work, the microgrid was often treated as a small sized conventional power grid where the failure modes of power electronic interfaces were not considered in microgrid reliability evaluation [29–33]. These methods may be practical for estimating microgrids with combined heat and power plants (CHPs) [34] or conventional generators, but are not suitable to analyze a distribution network with PVs or other renewable sources. The effect of converter topologies is incorporated into reliability evaluation of DC microgrid by the use of minimum cut sets [35]. This approach, however, neither considered the impact of power losses and ambient condition on converter reliability nor can be extended to distribution system reliability assessment. Ref. [36] has pointed out that modeling the operation mode transitions is a major challenge in reliability evaluation of microgrids. Reliability of PV/wind microgrid operating in an islanded mode was studied using Monte Carlo simulation [37]. Again, this approach only dealt with input power of PV array without considering the reliability of PV inverters. Fault Tree Analysis (FTA) has been used to evaluate the reliability of islanded microgrid in emergency mode [38]. The limitation is that this FTA approach can only compute small-scale systems and

cannot deal with interconnected modes. It has been realized that a multi-state model is needed for modeling PV generators due to the intermittent nature of solar radiation [39]. This method, however, neither considered the impact of input power and temperature on system reliability nor modeled islanded modes of PV microgrids. An analytical approach was proposed [40] to study the effect of distributed generators (DGs) on distribution reliability, where the DG outputs, DG failures and load variations were considered.

An event-based Monte Carlo method was developed [41] to evaluate the effect of intentional islanding and switching operations on distribution reliability. Furthermore, pseudo-sequential Monte Carlos has been adopted for the reliability of the active distribution networks [42]. The former approach is unable to deal with flexible operation modes of microgrids, and the latter assumes constant loads and DG outputs under islanding situations without considering the intermittent features of DGs.

PV sources have a wide range of application, ranging from small devices to large power systems. References [43, 44] examine the economic contribution of PV in an electrical power system. Reference [45] shows that at the current price, the economical analysis of connecting PV to the power system grid in an electric power system is cost-effective with government subsidy. Other study [46] found that 1 kW of PV generation can prevent between 700 g to 2300 kg of CO2 emission annually depending on the type of conventional fuel being offset. Similarly, the annual SO2 offset ranges from 4g/kW to 16 kg/kW of PV capacity. There is however relatively little work done on the reliability evaluation of power systems including PV generation.

Both analytical [47-49] and simulation [3, 4] methods have been used in the past to evaluate the reliability of PV integrated power systems. Simulation methods can incorporate many system complexities and chronology in the evaluation. These methods however require large amounts of data and are often very complex. Analytical methods are relatively simple and require less computation. These methods can be further developed to create techniques that provide reasonable accuracy and can be readily used in practical application.

Researchers have studied both large and small isolated power systems. A wide range of research has been conducted on the reliability contribution of solar energy in small isolated power systems. References [43, 50, and 51] present studies that show that there are considerable adequacy benefits associated with using solar energy in an electric power system. Solar energy is considered as an alternative source to meet the load energy demand in small isolated power systems in [52]. It is important to develop appropriate reliability models to easily evaluate the daytime reliability contribution of PV. The amount of sunlight at any geographical location highly depends on the latitude and on cloud cover. There is a lack of research on the impact of these factors on system reliability. It is therefore important to evaluate the reliability contribution of PV considering these factors.

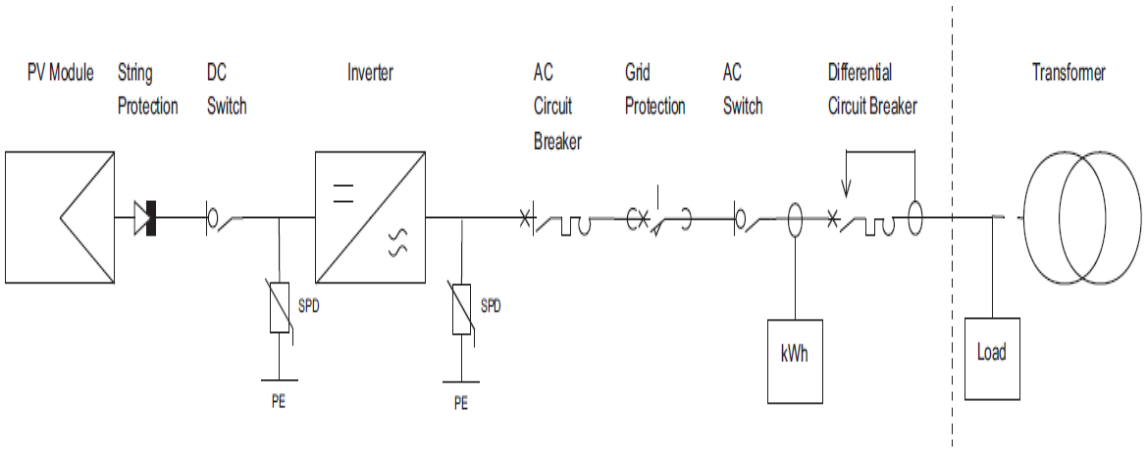

Fig 2.2 - Electrical architecture for the PV system.

The electrical architecture of a generic PV system integrated with grid is shown in Fig. 2.2. The PV module strings are connected to the inverter by means of a protection to assure that no inverse current is running in a string as a result of i.e. partial shading. In general, the protection can be: a blocking diode (as represented in Fig. 2.2), a fuse or a circuit breaker.

2.4 Power electronic components

Although the PV reliability issue was already identified three decades ago [53], reliability quantification of an entire PV generation station remains unresolved due to the

complex nature of PV systems. Fig 2.3 shows the different power electronics components which are used in a PV system The literature mostly focuses on reliability assessment for the power electronic components such as IGBT [54], capacitor [55] and inverter [56,57], whereas much fewer references discuss the reliability evaluation for entire PV system. Refs. [58, 59] presented simplified, system-level models for PV system Reliability using a Markov modeling concept. Hierarchical Reliability Block Diagram was developed [60] to model the behavior of PV system. Ref. [61] quantified the impact of inverter failures on total lifetime of PV system using Monte Carlo simulation. Ref. [62] proposed Latin Hypercube Sampling (LHS) technique to integrate stratified and random sampling in order to improve its computational speed for obtaining the reliability indices. In the paper, failure rates of electronic elements in a PV system are treated as constants. These parameters, however, actually vary with system states including solar insolation [63], ambient temperature [64], and load level [65]. The unrealistic assumptions in reliability analysis may give inaccurate or misleading results.

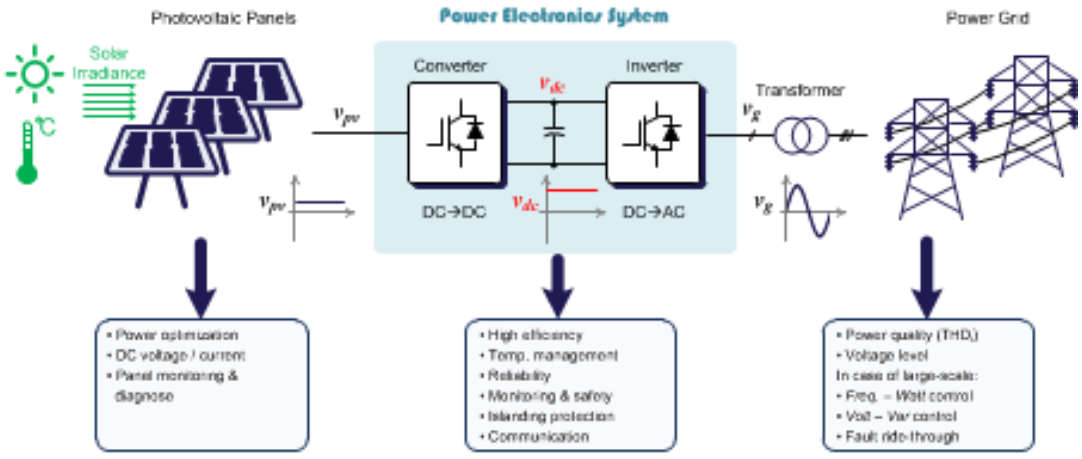

Fig 2.3 - Power electronics components which are used in a PV system.

3. Scope of the work

Reliability evaluation techniques are well developed and various papers, articles and books are published on this topic. Also, some commercially available computer programs have been developed for this purpose. Analytical and probabilistic techniques are in use for many decades. The development of reliability evaluation technique was associated with the aerospace industry and military applications. It was subsequently followed by applications in nuclear industry and electric power systems where system failure has large social and economic impacts. Various advances have been done in the methods of reliability evaluation such as Markov chain method and Monte Carlo sequential simulation method.

This research focuses on reliability evaluation of power system with distributed renewable generation. The system under study comprises of solar photovoltaic cells and conventional synchronous generators. Although, reliability evaluation solar photovoltaic power system has been carried in various countries, but enough attention has not been given in India towards this area. By using various available evaluation techniques on the data taken from various solar PV plants, the reliability of plants in India, can be evaluated which will further help in reduction of cost and improvement in efficiency of the power system.

The impetus is on analyzing and determining the contribution of a PV system to the overall system reliability. A major objective of the research is to develop appropriate models and methods for solar energy systems that can be utilized to evaluate the reliability of a power generating system containing PV. Another major objective is to investigate the effects of various key factors and elements associated with PV energy generation in terms of their impact on the overall system reliability. The evaluation of capacity credit of PV sources, and the impact of various system parameters on the capacity credit are also important targets of this research.

A determination of the capacity value of PV is important in system planning. The output of a PV source, however, varies throughout the day. Different seasons and the time of the day have significant impacts on the power output of a solar cell and therefore the impacts of these factors on system reliability have to be investigated. Different factors

that influence the contribution of PV are incorporated in the developed model and several case studies will be handled to illustrate the reliability contribution of adding PV to an electric power system.

On the basis of literature review, following are the proposed objectives of the research work to be done during the Ph.D. program.

1. To study effect of ageing of photovoltaic panels
2. To study effect of mismatching of photovoltaic modules
3. A Probabilistic Reliability Evaluation of a Power System Including Solar Photovoltaic Cell Generator.
4. To evaluate the reliability of large Solar Photovoltaic Arrays.
5. Reliability evaluation of central- inverter PV system

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